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NOTES ON THE STABILITY AND CONTROL OF TAILLESS AIRPLANES

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SUMMARY

Problems involved in the stability and control of tailless airplanes are discussed. Such factors as the location of the aerodynamic center and its effect on the longitudinal stability, longitudinal trim with high-lift devices, the effects of various changes in the shape of the wing on lateral stability, and the effects of nacelles are covered.

It appears that sufficient stability and controllability can be secured without sweepback. With sweepback, a flap over the center section of the wing may be used to serve the dual purpose of elevator control and high-lift device. Sweepback introduces undesirable stalling characteristics, however, and may require auxiliary devices to prevent stalling of the tips.

INTRODUCTION

The advantage in arrangement and performance that the tailless airplane has over the conventional type has already been the subject of considerable discussion. The present paper is chiefly concerned with aerodynamic factors as they affect the stability and control of tailless airplanes.

With the aerodynamic information available at present, the designer should be able to predict with confidence the behavior of an airplane that resembles in design a reasonably conventional wing. There is still, however, a lack of information on the loading of wings with large angles of sweepback and on the loading of wings of very low aspect ratio.

SYMBOLS

A aspect ratio

α angle of attack

b wing span

β angle of sideslip

c wing chord

$$C_L = \frac{\text{Lift}}{S_w \frac{\rho}{2} U_o^2}$$ lift coefficient

$$C_l = \frac{L}{S_w \frac{\rho}{2} U_o^2 b}$$ rolling-moment coefficient

$$C_m = \frac{M}{S_w \frac{\rho}{2} U_o^2 c}$$ pitching-moment coefficient

$$C_n = \frac{N}{S_w \frac{\rho}{2} U_o^2 b}$$ yawing-moment coefficient

$$C_Y = \frac{Y}{S_w \frac{\rho}{2} U_o^2}$$ side-force coefficient

$$C_{L_\alpha} = \frac{\partial C_L}{\partial \alpha},\quad C_{m_{D\theta}} = \frac{\partial C_m}{\partial D\theta}\ \frac{\partial C_m}{\partial \frac{qc}{U_o}},\ \text{etc.}$$

$$C_{n_r} = \frac{\partial C_n}{\partial \frac{rb}{U_o}},\quad C_{l_p} = \frac{\partial C_l}{\partial \frac{pb}{U_o}},\quad C_{l_\beta} = \frac{\partial C_l}{\partial \beta},\quad \text{etc.}$$

$D = \frac{d}{ds}$ derivative with respect to distance along flight path

δ	elevator or rudder deflection
k_X, k_Y, k_Z	radii of gyration about axis indicated by subscript
l	length of fuselage
m	mass of airplane
p	angular velocity in rolling
q	angular velocity in pitching
r	angular velocity in yawing
$s = \frac{U_o t}{c}$	distance along flight path
X, Y, Z	airplane axes

LONGITUDINAL STABILITY AND CONTROL

An ordinary wing with a slight reflex camber and dihedral has all the aerodynamic characteristics necessary for both lateral and longitudinal stability. As in the conventional airplane, longitudinal stability in gliding flight is practically assured if the center of gravity is located slightly ahead of the aerodynamic center of the wing (fig. 1). For wings of normal aspect ratio and dimensions the aerodynamic center is located at about 24 percent of the mean chord. At very low aspect ratios the aerodynamic center moves ahead and upward, and the attainment of stability and balance becomes more difficult. The location is also appreciably changed by the addition of a streamline nacelle or by sweepback. Changes in wing section generally have only a slight effect. An extreme reduction in thickness toward the trailing edge may cause a backward displacement of 2 or 3 percent. Conversely, it is possible to produce a forward shift of the same amount by abnormal thickening of the rear portion.

The addition of a streamline fuselage or nacelle causes a forward shift of the aerodynamic center, thus necessitating a more forward location of the center of gravity. Figure 2 (plotted from data given in reference 1) shows the movement of the aerodynamic center actually caused by a relatively large fuselage in combination with the wing. It will be noted that, when the wing intersection was near the nose of the fuselage, the interference was sufficient to nullify the unstable moment; that is, the aerodynamic center was not shifted. A comprehensive analysis of the effects of the fuselage and nacelles on both the longitudinal and the lateral stability parameters will be found in a recent article by Multhopp (reference 2).

The stability characteristics of a tailless airplane differ from those of a conventional airplane chiefly in the reduced kinematic damping of the pitching motion. Figure 3 shows the estimated damping coefficients

$$C_{m_{D\theta}} = \frac{\partial C_m}{\partial D\theta} = \frac{\partial C_m}{\partial \frac{qc}{U_o}} \tag{3}$$

for several airfoil arrangements. It is to be noted that the addition of the tail surface increases the kinematic damping nearly 10 times. Both theory and experiment indicate that the effect of the fuselage on the damping is not important. (The value of $\Delta C_{m_{D\theta}}$ is of the order of -0.2 for a fuselage of the proportions illustrated in fig. 2).

If the tailless airplane is statically stable (that is, has its center of gravity ahead of the aerodynamic center), the free rotations in pitch will be coupled with motions normal to the chord and the damping of these motions will be effective in reducing the pitching.

Figure 4 shows the calculated periods and rates of damping of the short-period longitudinal oscillations, for varying degrees of static stability. In addition to the reduced damping coefficient $\left(C_{m_{D\theta}} = -\frac{1}{2}\right)$, the all-wing airplane was assumed to have a reduced moment of inertia in pitch $\left(k_Y = \frac{1}{2} c\right)$. The curves shown apply to a wing chord of 10 feet at a loading of 20 pounds per square foot and are typical of the results of an extensive series of calculations. The dotted lines indicate locations of the center of gravity for aperiodic motion in this mode.

It is remarkable that, although the rotary damping coefficient $C_{n_{D\theta}}$ of the tailless airplane is only one-tenth that of the conventional airplane, the resultant damping of oscillations in flight is nearly as great. The additional damping is obtained through coupling with the vertical motion. The lack of direct damping appears to alter the sequence of the motions in such a way as to make this coupling more effective in the case of the tailless airplane.

In slow longitudinal motions involving changes of flight speed, the stability of the conventional airplane is usually impaired by the action of the slipstream on the tail surface. In the usual arrangement, the lift of the wings acts behind the center of gravity and a downward trimming load is carried by the tail surface, which is in the slipstream. Since the velocity in the slipstream tends to remain more nearly constant than the flight velocity, the forces on the wing and on the tail surfaces will not vary with flight speed in the same proportion. Thus if the airplane noses up and loses flying speed, the wings, having most of their area outside the slipstream, will lose lift at a rate greater than the rate of reduction of the downward trimming load and the airplane may continue to nose up in an unstable manner. The tailless arrangement affords a definite advantage in that such adverse effects can be easily eliminated.

In the gliding condition, the damping of the phugoid motion of a tailless airplane is less than that of a conventional airplane and there is, in general, somewhat greater likelihood of phugoid instability with the tailless airplane. (See fig. 5.) With power on, the conventional airplane is more unstable because of the destabilizing influence of the slipstream. Inasmuch as the period of this oscillation is very long and the damping slight in any case, the differences shown are considered unimportant.

A decided change in the character of the longitudinal motion will occur if the center of gravity is allowed to shift to a position behind the aerodynamic center. In this condition the rate of divergence of the tailless airplane is much more rapid than that of the conventional type and may become uncontrollable at relatively small negative values of $\overline{x}$. Figure 6 shows typical variations of the damping factors at small values of $\overline{x}$. As the condition of neutral static stability $(\overline{x} = 0)$ is approached, the complex roots are replaced by real roots, one of which becomes positive at $\bar{x} = 0$, indicating a rapid divergence of the tailless airplane in the region of static instability.

It should be possible to secure satisfactory longitudinal control with a straight wing simply by utilizing the pitching action of narrow flaps. Because trim at higher angles of attack would be attained by raising the flap and thus reducing the camber, the arrangement would entail some reduction in maximum lift, the amount depending on the degree of static stability. Figure 7 shows the elevator angles and corresponding reductions in $C_{L_{max}}$ for several flaps with a straight wing. The curves were based on the reductions in C_L (below $C_{L_{max}}$) and the pitching moments obtained in experiments with flaps. It is to be noted that the narrower flap is the more efficient (though less powerful) elevator. The computations were made for a rectangular wing of aspect ratio 6. Very high lift coefficients could be attained only with the aid of some device that did not displace the center of pressure.

Figure 8 shows elevator deflections necessary to produce a specified curvature of the flight path and illustrates the increased maneuverability of the tailless airplane. The elevators are designed to give equal pitching moments in order that both the conventional and the tailless airplanes would require the same elevator deflections to produce equal changes in trim. The increased path curvature or normal acceleration possible with the tailless airplane is a consequence of the smaller damping in pitching.

If sufficient sweepback is employed, it becomes possible to use cambered sections or sections with flaps designed to increase the lift over the center sections of the wing. In such an arrangement the lift developed by the flap or by the camber is placed sufficiently far ahead to offset the pitching moment. Furthermore, if the flapped portion of the wing is placed somewhat farther ahead, so as to bring the centroid of its load forward of the center of gravity, the flap may be used directly as an elevator. (See fig. 9.) Downward deflection of the flap will then increase the lift and the angle of attack simultaneously, as illustrated in figure 10.

If the angle of sweepback is small, it may be assumed that the spanwise loading is not altered but is merely rotated backward through the angle of sweep. The pitching moment due to a small amount of sweep thus depends on the spanwise location of the load centroid of the straight wing. Figure 11 shows the calculated locations of this centroid corresponding to flaps of various lengths extending from the middle of the wing. The centroid for a flap of 100-percent span is the same as that for a change in angle of attack of the wing as a whole and thus locates the spanwise position of the aerodynamic center. It is preferable to assume that the lift loads act along the quarter-chord line and to take account of the backward displacement of the flap lift load by calculating the integrated pitching moment of the flapped sections, because this moment is more independent of aspect-ratio effects than is the lift. For rough estimates, the lift added by the flap may be assumed to act at about 45 percent of the chord of those sections inboard of the flap tip and along the quarter-chord line outboard of the flap tip.

A small damping coefficient $C_{m_{D\theta}}$ is a definite advantage in that the pitching disturbances produced by gusts are smaller. According to calculations made by Küssner (reference 3), a straight wing moving into an increasing gust will experience no pitching moment whatever about the quarter-chord line. Although it might be expected that the nose of the wing, being in a region of greater velocity than the rest of the wing, would be deflected upward, there will be at the same time an acceleration of the average normal velocity over the entire chord, which will lead to an aerodynamic inertia force acting at the 50-percent-chord point and which, calculations show, is just sufficient to balance the moments about the aerodynamic center. The argument may be extended to include any arbitrary variation of vertical velocity along the path of the airplane.

Because the wing will actually have its center of gravity ahead of the aerodynamic center for stability, it follows that the action of a rising gust will be to reduce the angle of attack and thus automatically to diminish the force of the gust. In figure 12 are plotted some curves, calculated by the method of reference 4, to show the effect of a gust on tailless and conventional airplanes. The gust was assumed to have uniformly increasing velocity. In the case of the conventional airplane, the initial pitching motion is in a direction that increases the angle of-attack because of the difference in the gust velocities at the wing and at the tail.

LATERAL STABILITY AND CONTROL

With careful design, the tailless airplane should be able to approach the conventional airplane in its lateral stability and control characteristics. The main difficulty is undoubtedly in the provision of sufficient weathercock stability and damping in yawing. The required degree of such stability is essentially the same as that for a conventional airplane and in either case is greatly reduced if the adverse yaw of the ailerons is eliminated. For this reason it seems desirable to use a lateral control having a zero or a slightly favorable yawing action. Favorable action is probably best achieved by a linkage between the aileron and the rudder controls or by a linkage between the ailerons and a servo tab on the rudder. With the aileron yaw compensated, the fin area required will be about in proportion to the size of the nacelles because the wing alone has marginal weathercock stability and damping. The unstable moment of the nacelles may be estimated by Munk's formulas (reference 5).

Different static yawing-moment characteristics may be obtained by altering the plan and elevation shapes of the wing. Changes of plan form alone do not, however, have a pronounced effect on the lateral-stability characteristics except insofar as they modify the stalling behavior of the wing. Weathercock stability may be secured by the use of sweepback combined with negative dihedral or with end plates at the tips. The negative-dihedral arrangement results in a favorable combination of rolling and yawing moments if the control is made to act on the turned-down tips. The yawing moment due to the rolling motion produced is adverse, however, and of such magnitude as to counteract the favorable effect, unless extreme negative dihedral is employed. If extreme negative dihedral is used, the controllers on the tips act primarily as rudders and separate ailerons must be provided on the main wing surface. The tips then correspond to end plates on the under side of the wing.

End plates on the under side of the wing will experience an outward force as a continuation of the lift of the wing. It might be thought that the outward lift of such end plates would be unfavorable to weathercock stability, because a sideslip would increase the lift, and hence the drag, on the down-wind plate. In the true resolution of forces, however, it is found that the resultant tends to turn, maintaining a direction nearly enough at right angles to the wind to outweigh the drag increase. There is, therefore, actually a favorable weathercock action, as shown in figure 13. Similar considerations apply in determining the yawing moment of a wing with dihedral. In this case the customary setting, which inclines the lift inward, results in adverse weathercock action. For a more complete analysis of the lateral-stability characteristics of wings, the reader is referred to reference 6.

The requirement of dihedral for stability is essentially the same for a tailless airplane as for a conventional airplane. If spiral stability is not considered essential at all speeds (as is usually the case), it seems advisable to limit the dihedral to 1° or 2° in order to reduce lateral oscillations in rough air.

As in the case of pitching motion, elimination of the tail greatly reduces the rotational damping. Figure 14 shows the estimated damping coefficients of yawing motion $C_{n_r} = \dfrac{\partial C_n}{\partial \frac{rb}{U_o}}$ for some typical arrangements. The damping of a well-streamlined fuselage of round or oval cross section will be very small. One set of oscillation experiments gave a value equivalent to $C_{n_r} = -0.005$ for a fuselage having a length equal to two-thirds the wing span. In this case, however, the fuselage terminated in a vertical wedge, a feature which may well have accounted for the greater part of its damping. The damping of the wing is due to the distribution of drag along the span and becomes greater at higher lift coefficients. Within the usual limits of dihedral and weathercock effects, the damping of the free lateral oscillations is invariably greater than is indicated by the damping of pure yawing motion alone C_{n_r}. The additional damping is provided by C_{Y_β} and C_{l_p} and is introduced through the coupling of these motions (sideslipping and rolling) with the yawing motion. Because both C_{Y_β} and C_{n_r} as well as the coupling between yawing and rolling motions tend to diminish at lower angles of attack, the lateral oscillation is more likely to be troublesome at high speed. Figure 15 shows calculated rates of damping of the free lateral oscillations for typical values of the stability derivatives. The value of C_{l_β} used corresponds to a dihedral angle of approximately 2°. An indication of the variation of lateral stability with C_{n_β} and C_{l_β} at low values of C_{n_r} may be obtained from the charts given in reference 7.

If sweepback is employed, the fact should be borne in mind that a pronounced rolling or pitching instability may develop at high angles of attack because of premature tip stalling associated with a lateral flow of the boundary layer. The effect of sweep is to introduce a component of the relatively great chordwise pressure gradient into a direction at right angles to the main stream velocity over the wing. The viscous drag of the stream then cannot act to prevent flow of the boundary layer laterally into regions of lower pressure over the forward portions of adjacent wing sections. The result is that the boundary layer flows toward the tips of a swept-back wing and premature separation occurs. Figure 16, plotted from data given in reference 8, shows this effect on sections near the tips of two rectangular wings with sweep. The existence of this effect may also be inferred from the tests of reference 9, in which the swept-back wings tended to nose up when stalled. (See fig. 17.) With 30° sweepback this tendency persisted even when the wing was given 8.5° washout. Little is known about the variation with angle of sweep, although the tests of reference 9 showed an appreciable effect at an angle of 15°. From these indications, it would seem advisable to incorporate some auxiliary boundary-layer control device, such as leading-edge slots, in the design of a tailless airplane having considerable sweepback.

CONCLUSIONS

1. With careful design it should be possible to secure satisfactory stability and control in a tailless airplane. The small rotational damping hardly affects the short-period longitudinal oscillations, although the damping of the stable lateral oscillation is likely to be reduced somewhat, particularly at high speeds.

2. Although the damping in pitching has a small effect on the stability with normal center-of-gravity locations, the tailless airplane is in greater danger of in-

stability due to an abnormal backward shift of the center of gravity because this instability becomes more serious as the damping is reduced.

3. As the weathercock stability or the damping in yawing is reduced by elimination of the tail surfaces, it becomes more important to overcome the aileron yaw and the yaw due to rolling.

4. A considerable reduction of the disturbances produced by vertical gusts is possible in the case of a tailless airplane without sweepback. This effect, which is due to a favorable pitching motion, depends on the static stability and the moment of inertia of the airplane.

5. The use of sweepback makes it possible to employ a partial-span flap as a high-lift device. It also simplifies the problem of securing weathercock stability and damping in yawing. Wind-tunnel tests of wings with sweepback show, however, that it is necessary to guard against a pronounced rolling and pitching instability near the stall.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., October 2, 1941.

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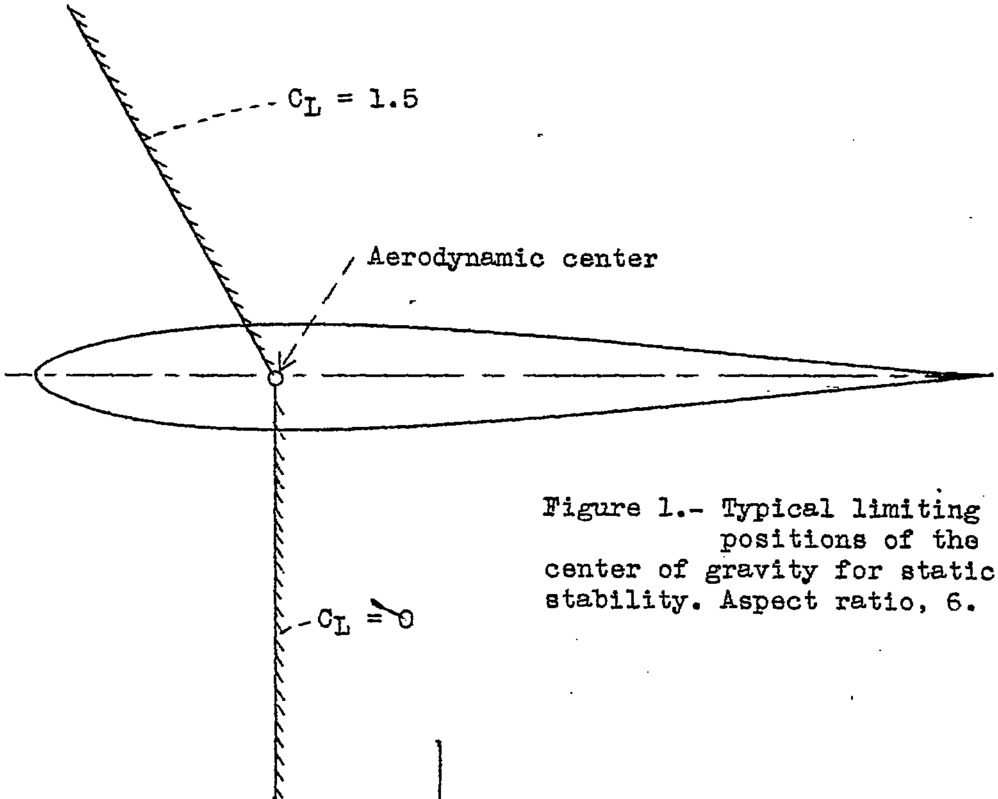

Figure 1.- Typical limiting positions of the center of gravity for static stability. Aspect ratio, 6.

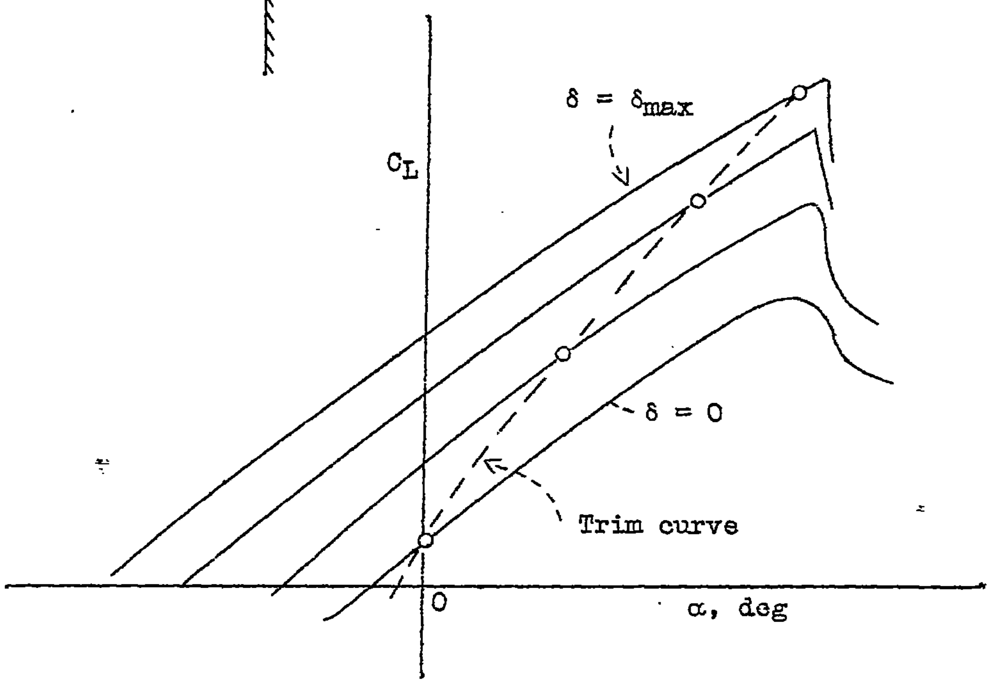

Figure 10.- Simultaneous change in lift and angle of attack produced by a flap on a wing with sweepback.

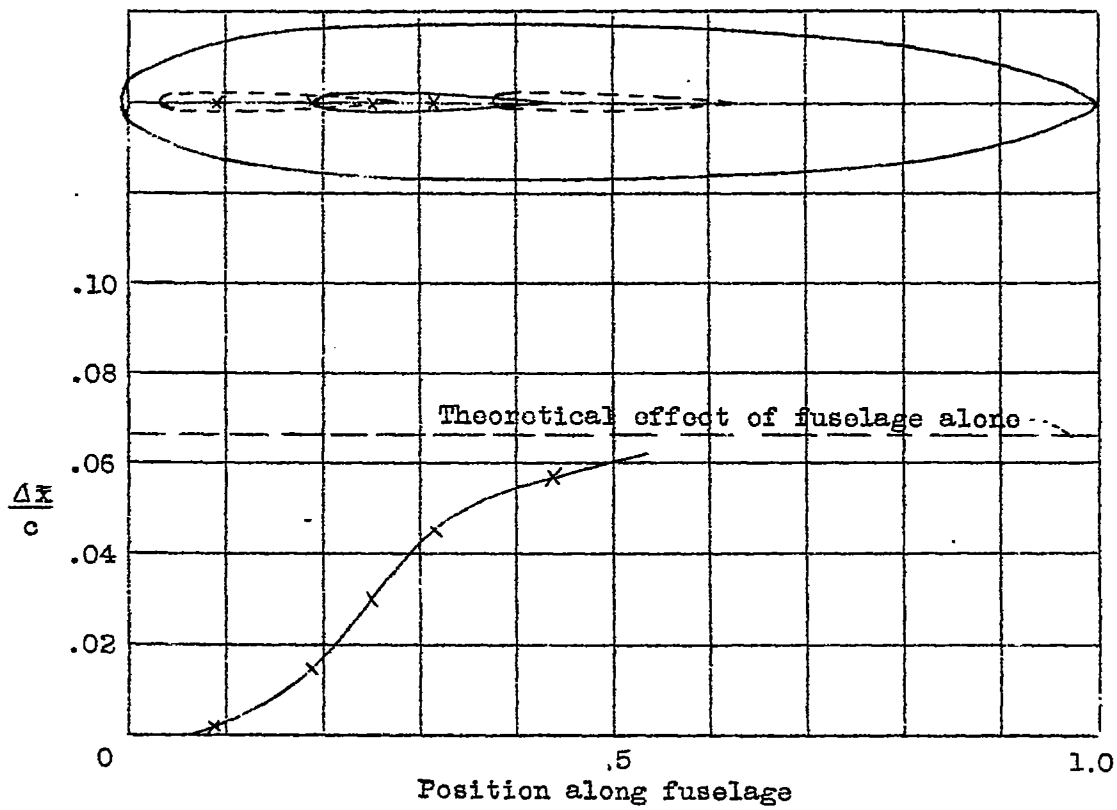

Figure 2.- Forward displacement of the aerodynamic center caused by the fuselage in combination with the wing. Wing span, 1.5. Data from reference 1.

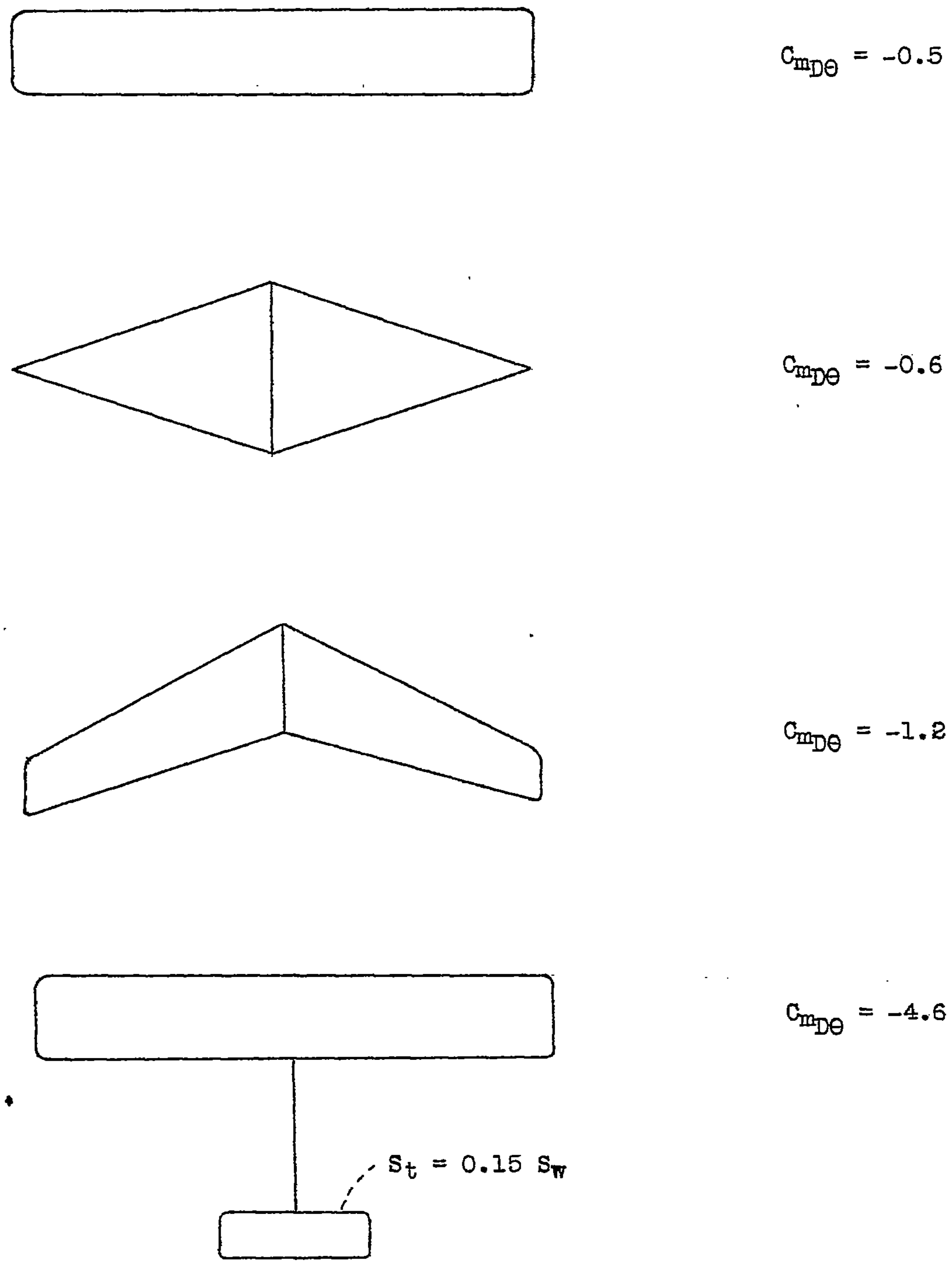

Figure 3.- Representative damping coefficients. $C_{m_{D\theta}} = \dfrac{\partial C_m}{\partial \frac{qc}{U_o}}$

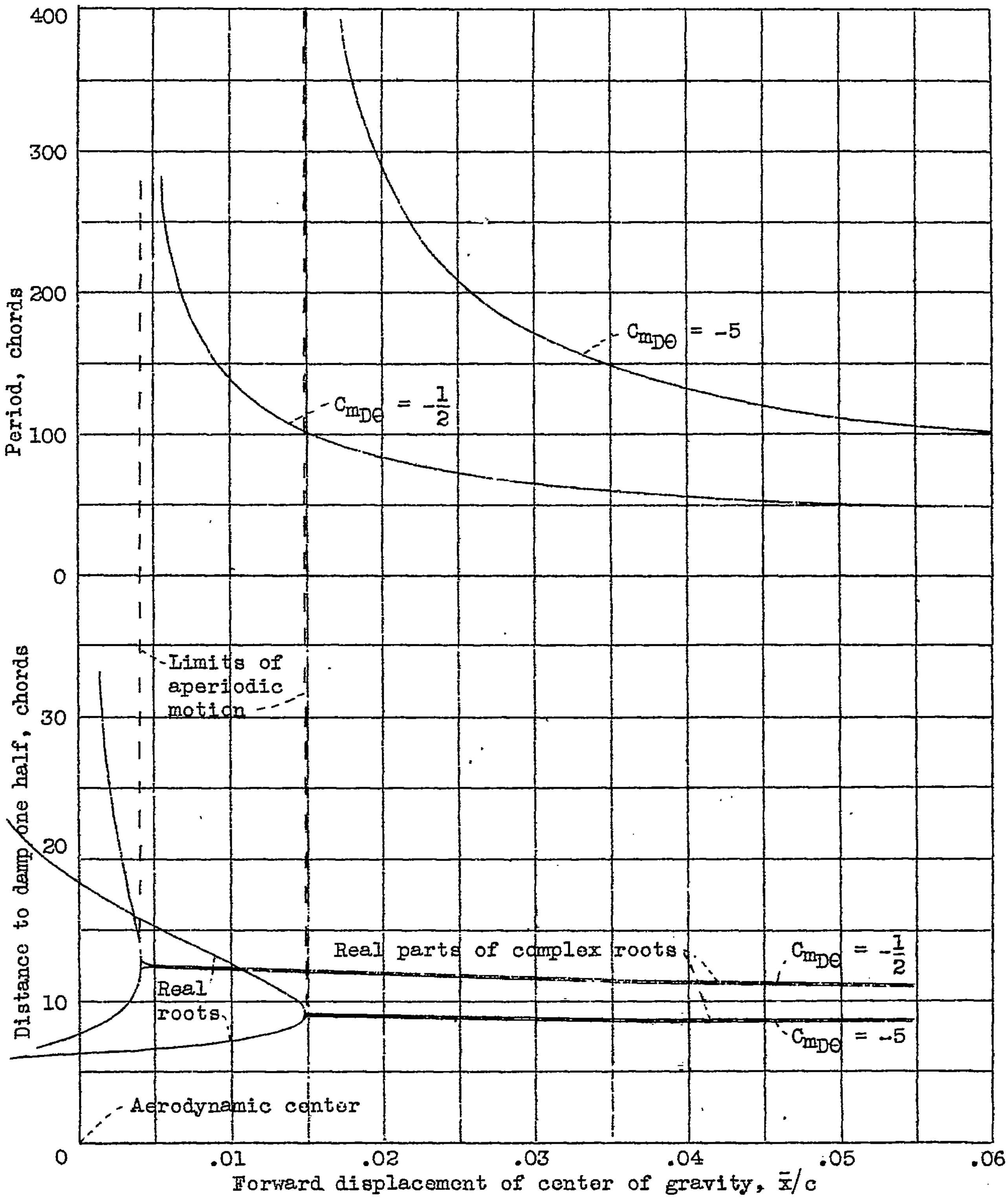

Figure 4.- Characteristics of the short-period longitudinal oscillation.

$$\frac{m}{S\frac{\rho}{2}c} = 50$$

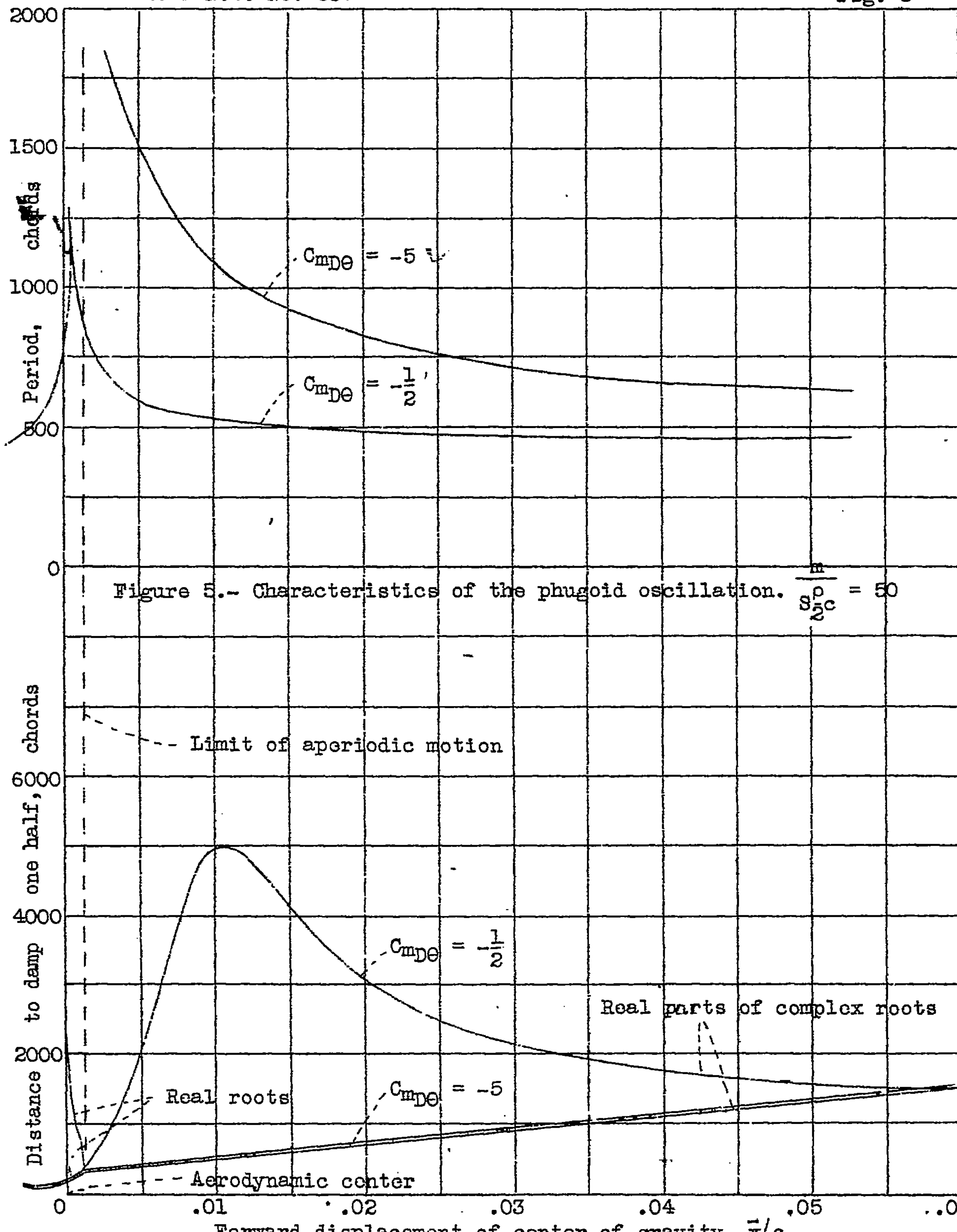

Figure 5.- Characteristics of the phugoid oscillation. $\frac{m}{S\frac{\rho}{2}c} = 50$

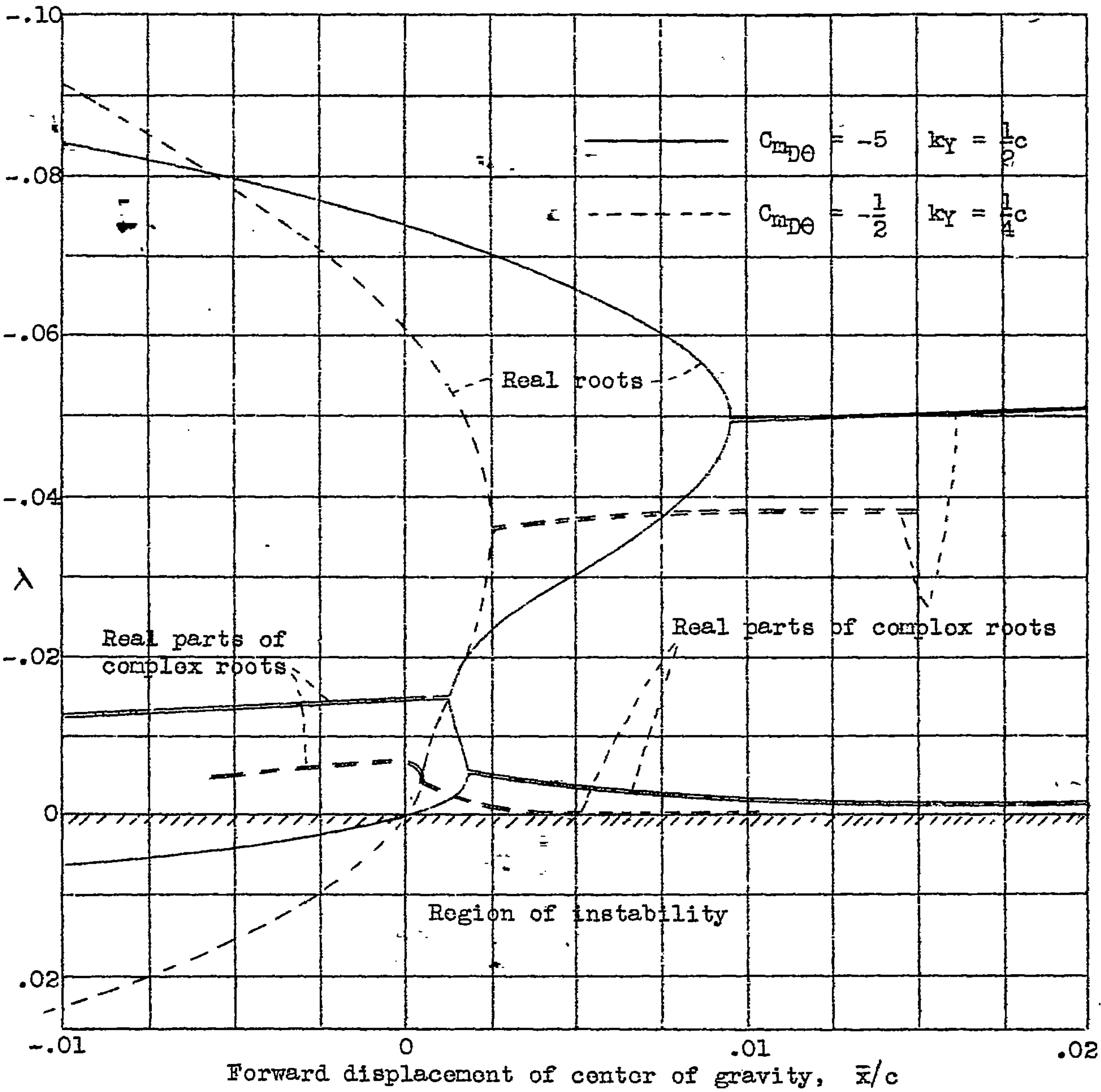

Figure 6.- Variations of stability with small displacements of the center of gravity from the aerodynamic center. Root of stability equation, λ; $\frac{m}{S\frac{\rho}{2}c} = 150$; $C_L = 2.0$.

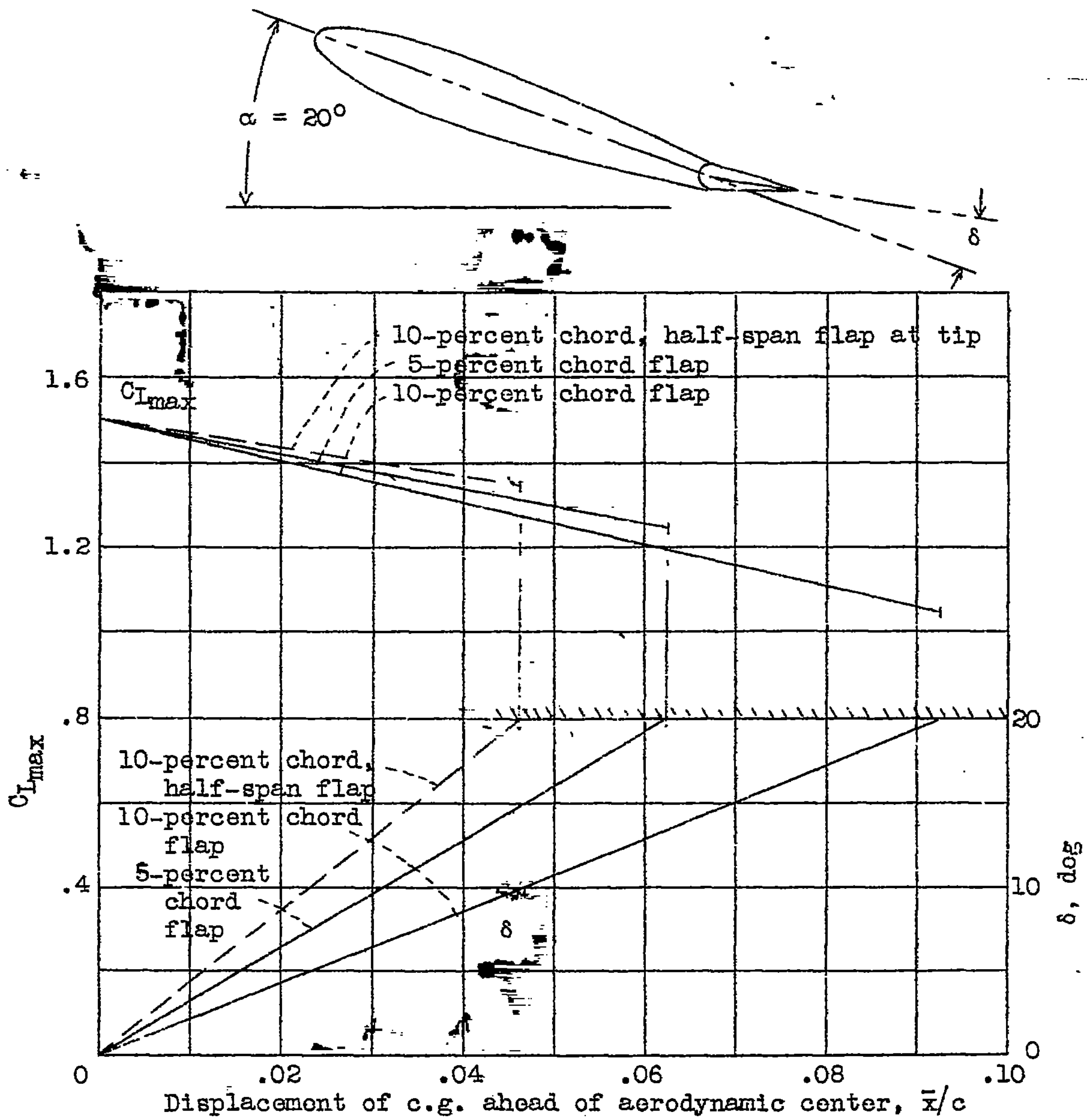

Figure 7.- Elevator deflections and corresponding reductions in $C_{L_{max}}$ for trim at $\alpha = 20°$. Rectangular wing, aspect ratio, 6.

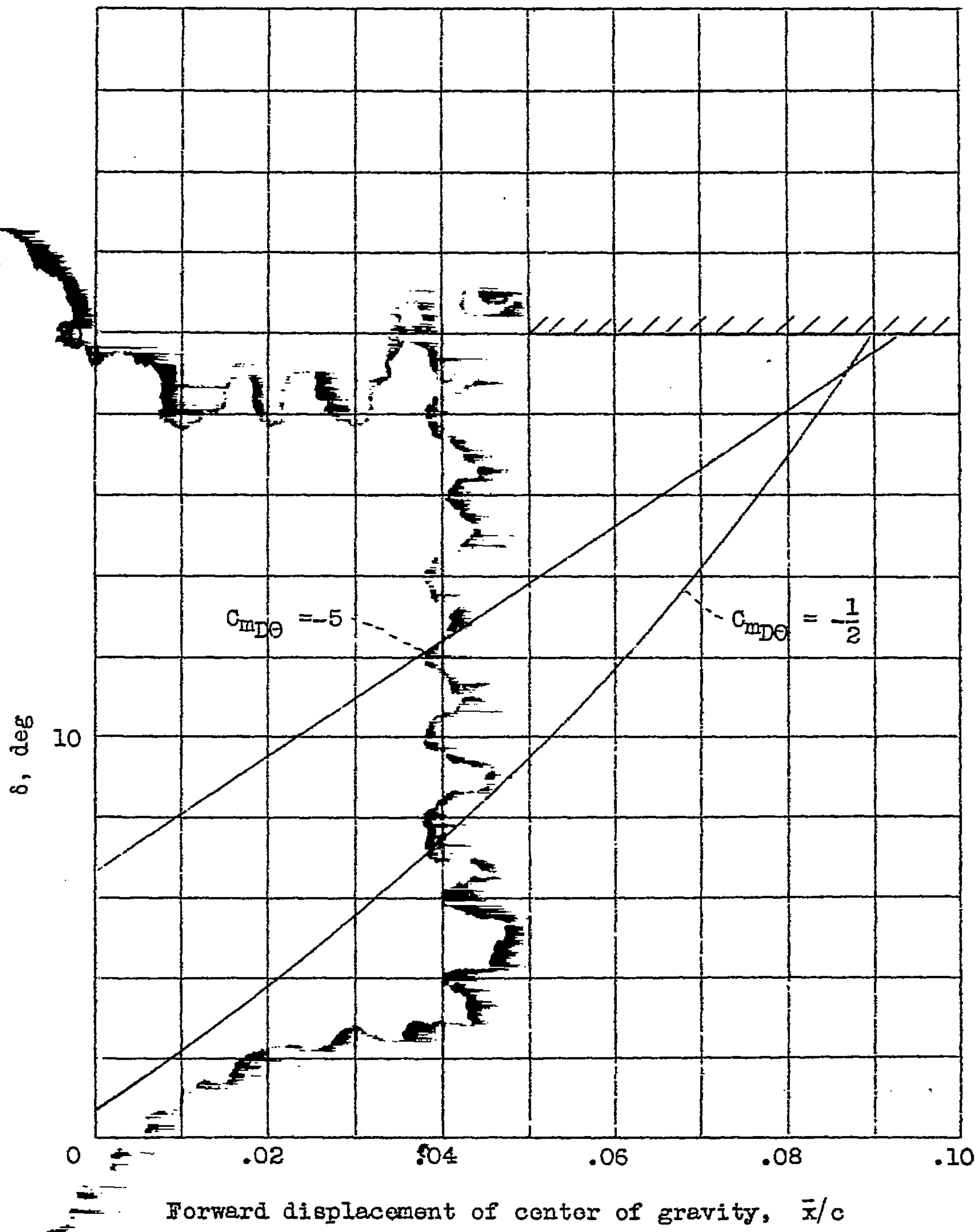

Figure 8.- Typical elevator deflections required to produce specified acceleration in pull-up. (Elevators designed to give equal pitching moments.)

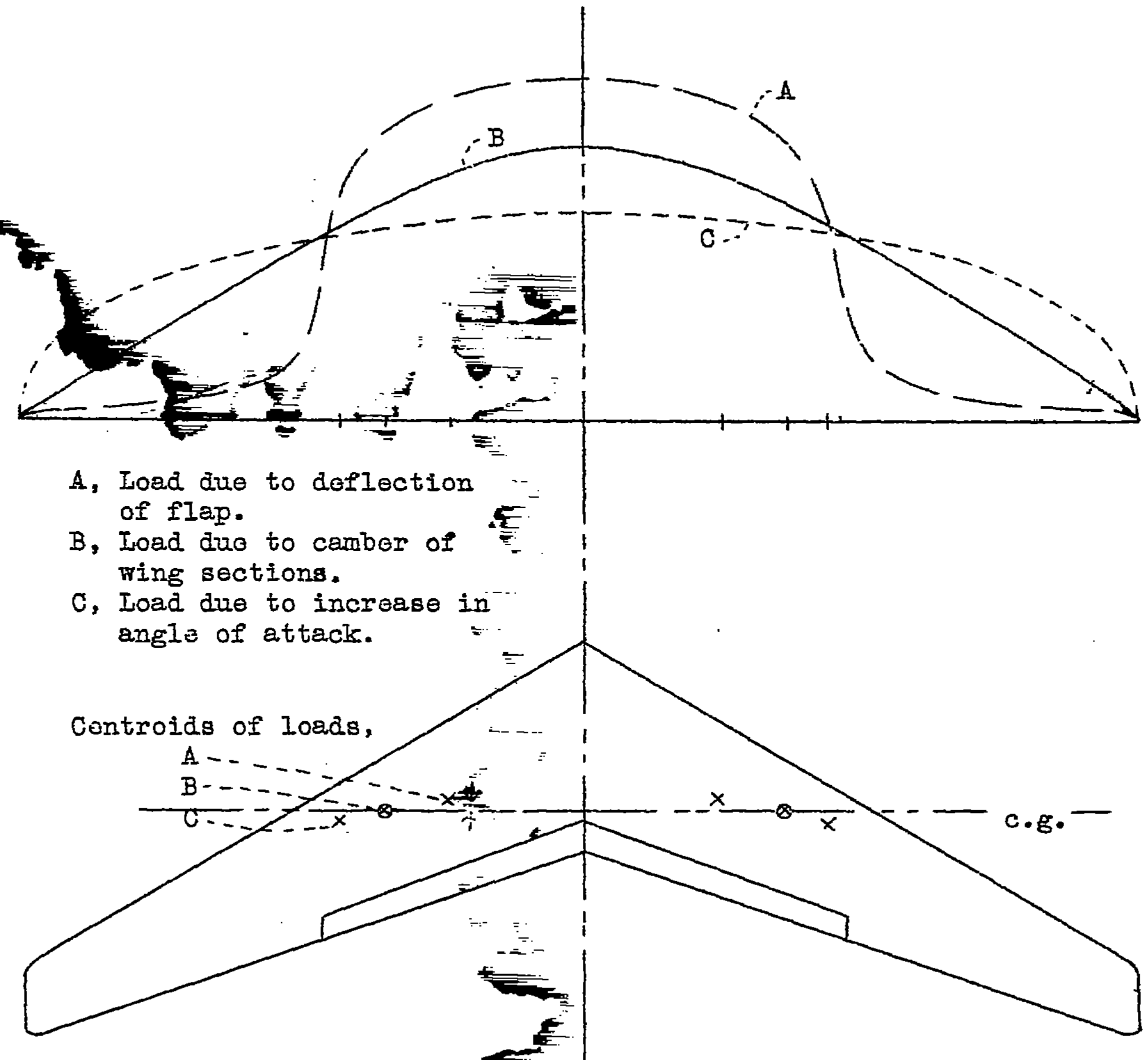

Figure 9.- Diagram illustrating the use of sweepback to secure trim with a partial-span flap.

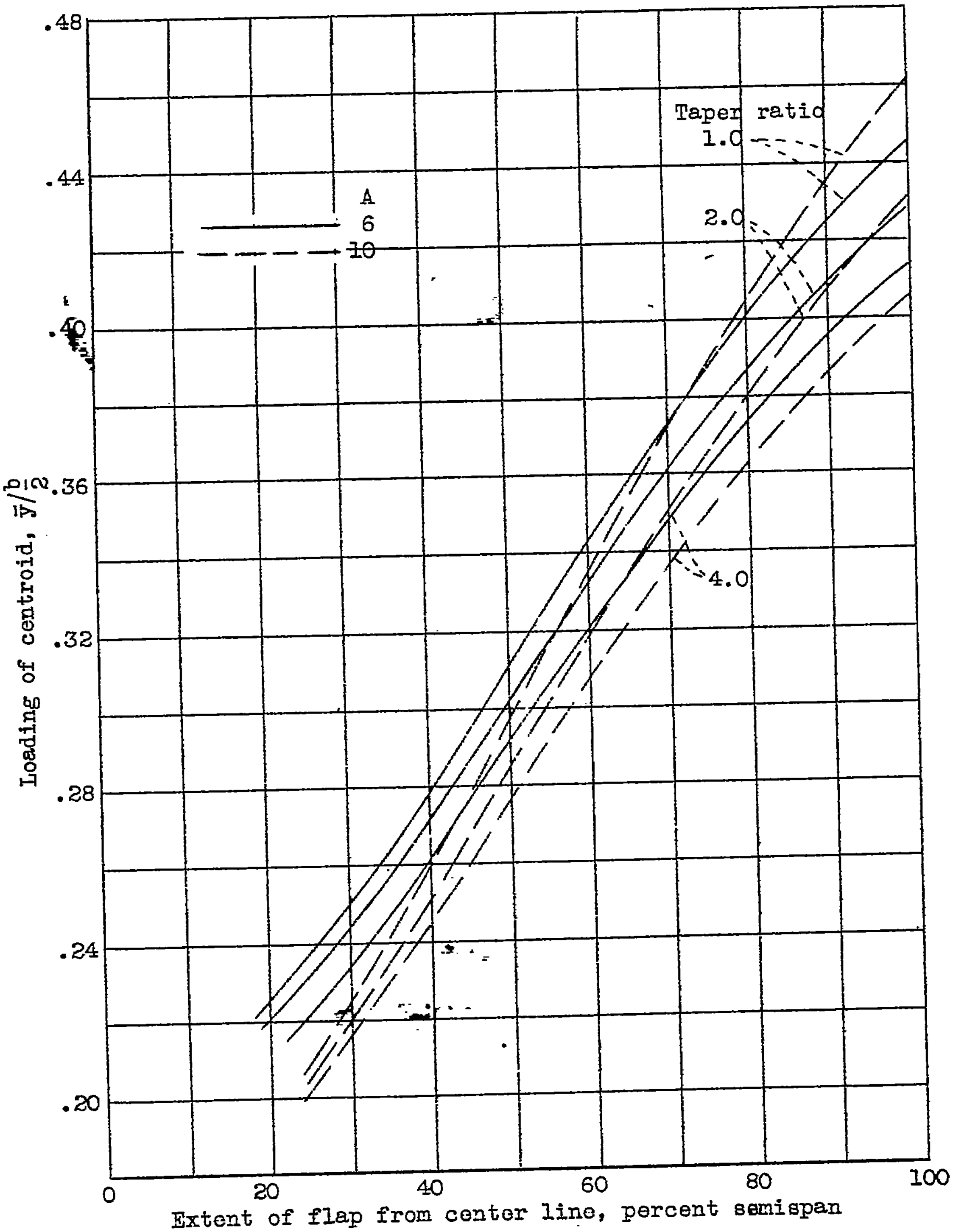

Figure 11.- Spanwise location of the centroid of the loading due to deflection of partial-span flaps. (Loading A, figure 9.)

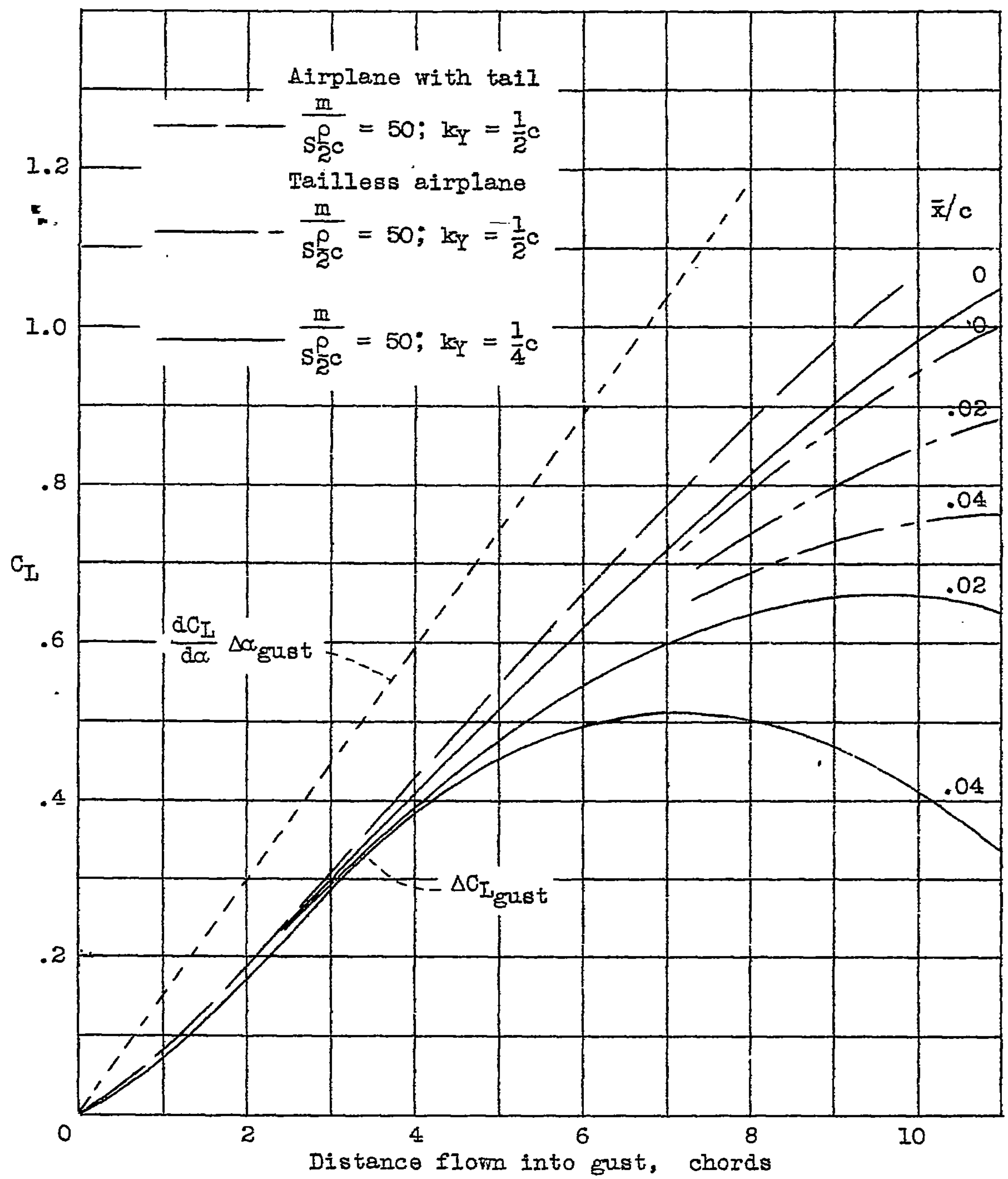

Figure 12.- Gust-alleviating action due to pitching motion and to lag in the development of lift.

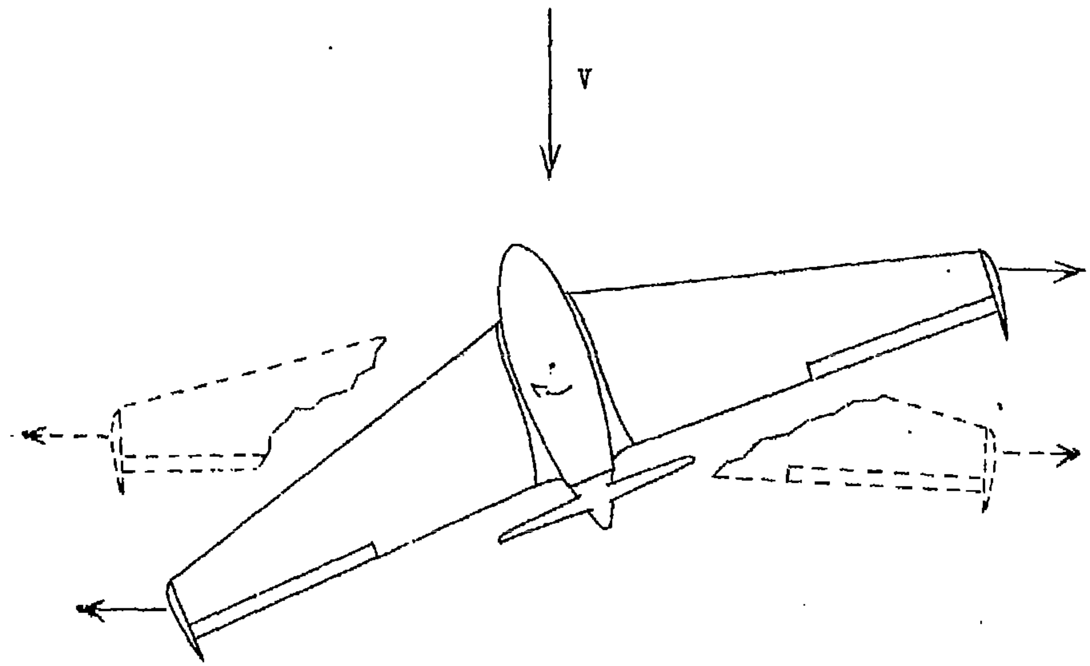

Figure 13.- Weathercock action of end plates set to give outward lift.

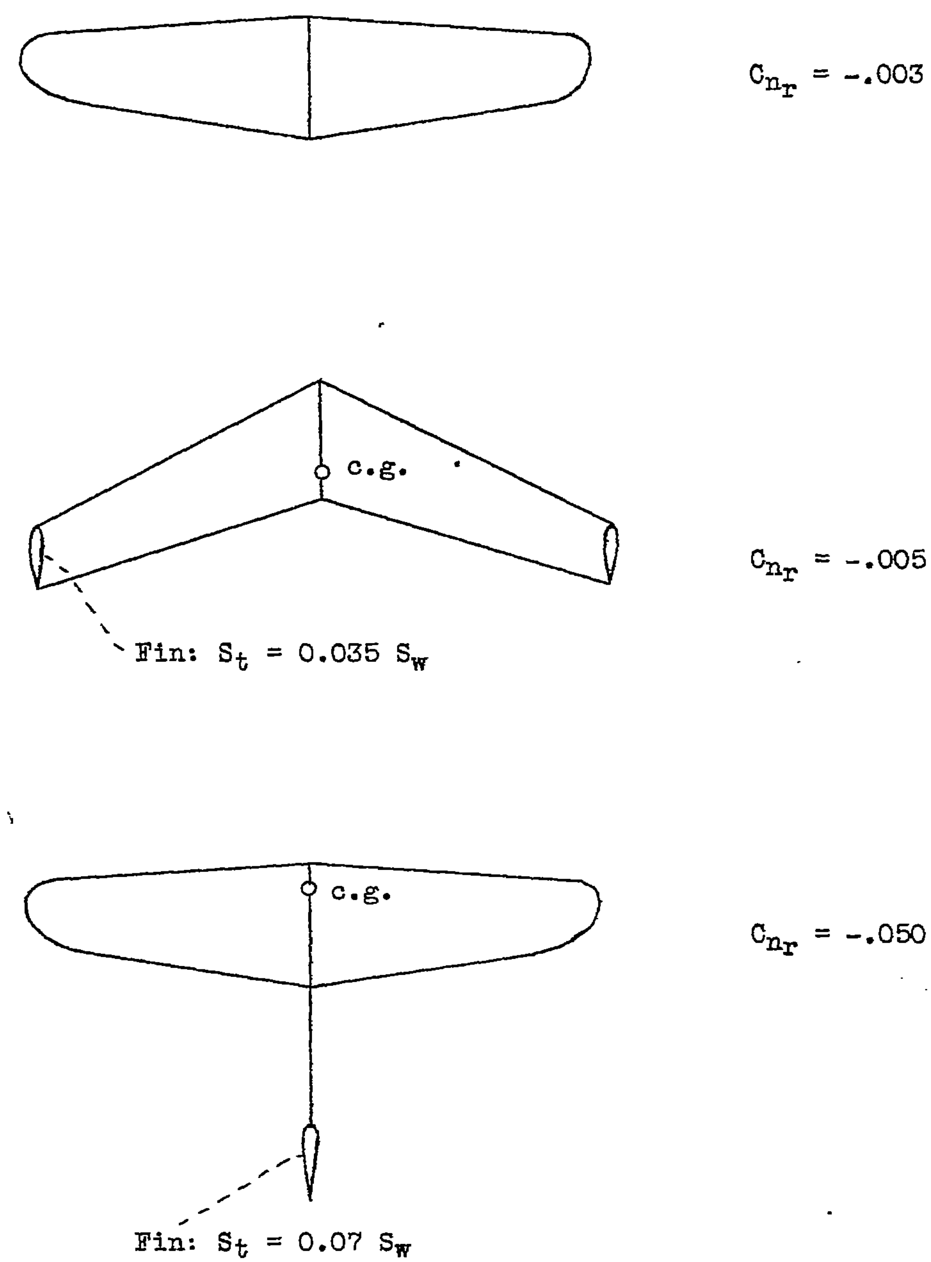

Figure 14.- Representative damping coefficients. $C_{n_r} = \dfrac{\partial C_n}{\partial \frac{rb}{U_o}}$

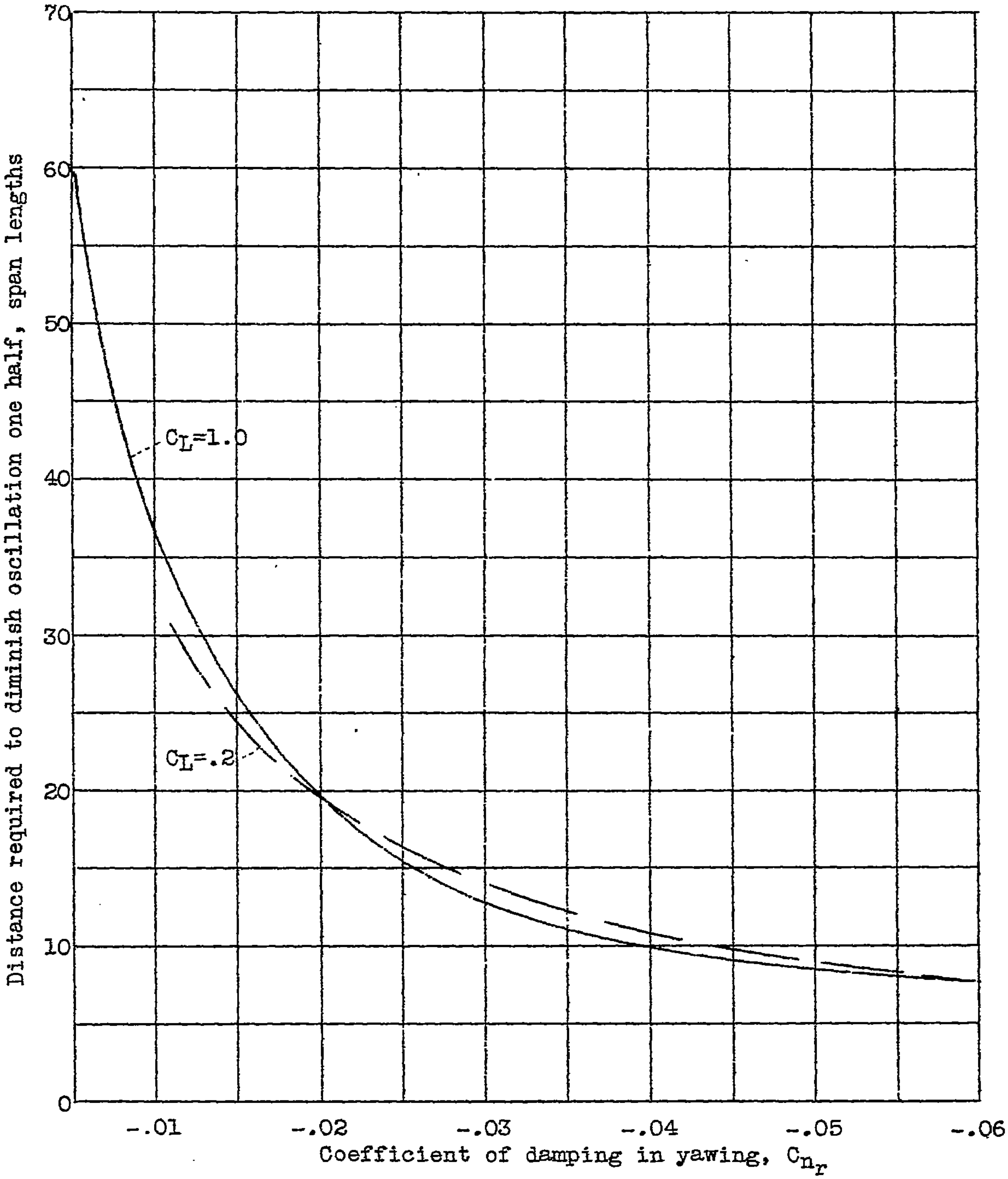

Figure 15.- Variation of damping of lateral oscillations with C_{n_r}.

$$\frac{m}{S\frac{\rho}{2}b} = 8\frac{1}{3}\ ; \quad \frac{k_X}{b} = \frac{1}{8}\ ; \quad \frac{k_Z}{b} = \frac{1}{7}\ ; \quad C_{l_\beta} = -0.026\ ; \quad C_{n_\beta} = 0.020\ .$$

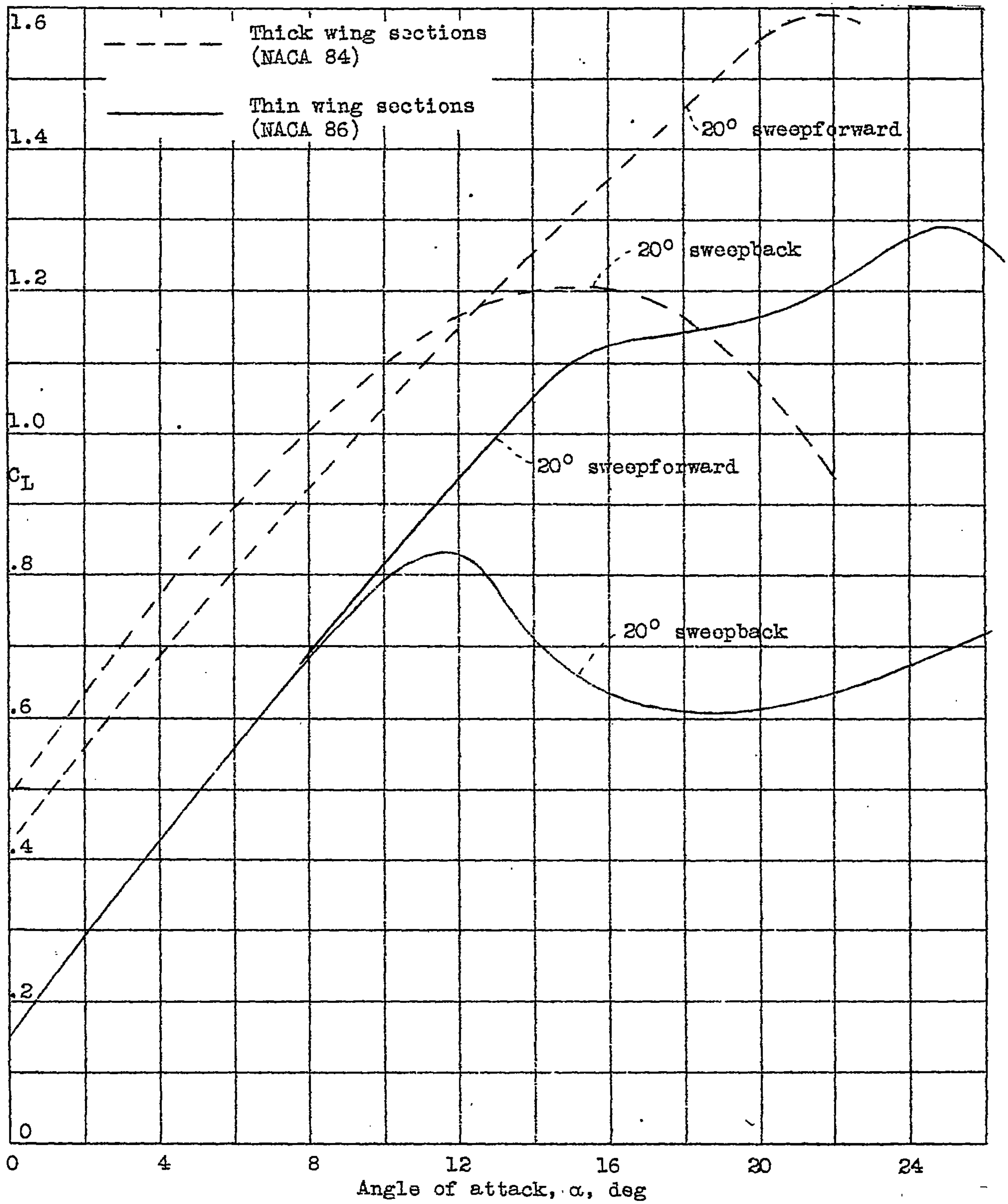

Figure 16.- Effect of sweep on the lift of a wing section near the tip (80 percent semispan stations). Data from reference 8.

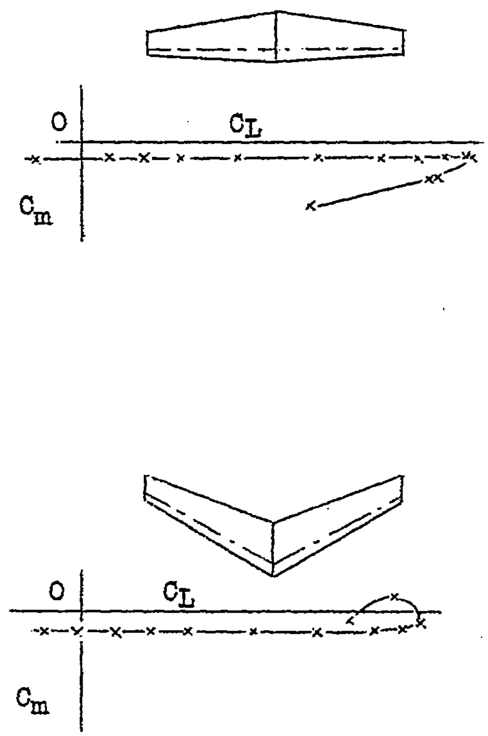

Figure 17.- Test results showing pitching instability of swept-back wing at $C_{L_{max}}$. Data from reference 9.